DARPA WORKSHOP ON GEOTHERMAL ENERGY FOR MILITARY OPERATIONS

DRP90T1

LMI

MAY 2010

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REPORT DRP90T1

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Executive Summary

The Defense Advanced Research Projects Agency (DARPA) sponsored a workshop March 23–25, 2010, to investigate the development of geothermal energy technology for use by the U.S. military. The acquisition of energy is problematic for the Department of Defense (DoD) for a number of reasons, and DARPA does not now invest in geothermal technology.

Geothermal energy is an attractive form of renewable energy because it provides a continuous flow of heat and hence can be used for base load power supply. Its greenhouse gas and other emissions are minimal, making it environmentally acceptable. To date, the resource has not been much exploited because conventional technologies are constrained to specific geologies, and newer, enhanced geothermal technologies are risky and costly. The workshop was convened to explore whether investment in advanced geothermal technologies might reduce the risk and cost to the point where the U.S. military would be able to take advantage.

Supplying geothermal energy to expeditionary forces poses several challenges. Standard exploratory techniques involve putting geologists on the ground and digging exploratory wells. Where geothermal resources show high potential, production wells must be dug and power plants erected. Geothermal power plants and the required cooling towers take up considerable space. The process of exploration, drilling, and power plant construction may require several months and considerable logistics support. The logistics and time associated with geothermal power are formidable barriers to DoD use.

Advances in geothermal technology could ease some of these challenges. Remote sensing might obviate the need for geologists on the ground. Automated drilling and hybrid drilling might reduce the logistics and time needed to drill wells. Better fracture mapping and fluid qualities could help reduce the uncertainty of drilling and enhance heat transfer capabilities. More productive ways to use waste heat would reduce the need for cooling towers and increase the efficiency of the power production process. Any of these advances also would assist in the application of geothermal energy in civilian use.

Advances in enhanced geothermal systems (EGSs) could be of substantial military value because they would broaden the geographic application of geothermal energy. Workshop participants identified a number of technological challenges and outlined possible solutions:

- Better resolution and accuracy of underground images from seismic monitoring
- Improved capability of microseismic tools to withstand down-hole heat and moisture
- Use of smart tracers and reactive tracers to interrogate the fracture structure at a particular location
- More accurate directional drilling and enhanced horizontal drilling capability
- Measurement while drilling by, for example, using wired drill pipe or fiber-optic drill string with the ability to transmit down-hole fracture and heat reservoir information to the surface.

Ground source heat pump technology may have immediate application to some expeditionary missions and many fixed installations. Although technical advancements may help with this technology, a more basic need appears to be demonstrations under varying conditions to see whether it can be practically applied and is cost-effective.

A proposed move of U.S. forces from Okinawa to Guam will significantly increase demand on the island's limited power grid. For that reason, among others, geothermal energy could have high military value on Guam. The most pressing need is to investigate the heat gradient of the island subsurface and the potential for geothermal energy by drilling a temperature gradient well. For a number of reasons, DoD investment in such investigation appears to have significant payoff.

The results of the workshop indicate that geothermal energy holds promise for military use under a variety of circumstances. Technological challenges, many of which were identified at the workshop, delay widespread application. The most relevant solutions from a DoD perspective likely are the advancement of EGSs, particularly through improvements in sensor and automation technologies, and the means to increase the efficiency of geothermal power production while decreasing its footprint. Other, more immediate applications for military purposes, such as ground source heat pumps and geothermal power on Guam, appear to be more matters of investigation and assessment than of technical progress, though advances in the technologies associated with these applications certainly would be helpful and render them more attractive than otherwise.

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Chapter 1
Introduction

The Defense Advanced Research Projects Agency (DARPA) sponsored a workshop March 23–25, 2010, at LMI headquarters in McLean, VA, to investigate the development of geothermal energy technology for use by the U.S. military. The acquisition of energy is problematic for the Department of Defense (DoD) for a number of reasons, and DARPA does not now invest in geothermal technology. To see whether it should, DARPA initiated the workshop to seek advice from several of the country's leading geothermal experts.

Approximately 40 experts in geothermal energy attended the workshop. It featured several plenary sessions, during which people with expertise in military energy use and geothermal technology made presentations. It also featured "lightning" sessions, during which people with particular technological approaches to the exploitation of geothermal energy presented their ideas. These were followed by eight breakout sessions, in which particular aspects of geothermal energy were discussed and technological challenges identified. The workshop ended with a general discussion of the challenges and DARPA's possible role going forward to address some of them.

MILITARY CHALLENGES CONCERNING ENERGY

The U.S. armed forces require energy for almost everything they do. Military installations consume large quantities of power, and operating forces consume fuel, power, and water, which have to be delivered to wherever they are sent. The workshop was informed that the full cost of delivering fuel to the frontlines in Afghanistan is more than $10 per gallon and that the full cost of delivering water there is almost $5 per gallon. The full cost of fuel or water includes the military logistics used to move these resources to the frontlines and to protect the resources that move them.

The workshop was further informed that the full cost of providing power to a forward operating base (FOB) via a 5 kW generator is as high as $4.00 per kWh in a medium-intensity conflict, as high as $1.70 per kWh for a 60 kW generator. These numbers suggest that geothermal energy—if it could be supplied to an FOB in a timely, practical fashion—could dramatically reduce operating costs.

Geothermal energy also could be of substantial military value to U.S. installations worldwide. A recent Defense Science Board report emphasized the dependence of U.S. installations on the power grids to which they are connected and their

vulnerability to long-term disruption of those grids.[1] Geothermal power may offer an alternative to grid-provided electricity in some cases. Moreover, ground source heating and cooling is available everywhere and under certain conditions might significantly reduce the need for externally fueled power.

A recent specific challenge concerns the Island of Guam. The U.S. military will be moving some 20,000–25,000 personnel and their dependents to Guam over the next several years. Another 10,000 or so support personnel are expected to move there as well. Because the present population of the island is only around 175,000, this represents a large increase. The demand for energy and water on Guam will expand and likely stress the island's limited natural resources. However, Guam is situated in a region of volcanic activity, which often is associated with the availability of geothermal energy. For these reasons, a portion of the workshop focused on Guam. Lessons learned from use of geothermal energy on that island would likely apply elsewhere as well.

Geothermal energy is an attractive form of renewable energy because it provides a continuous flow of heat and hence can be used for base load power supply. Its greenhouse gas and other emissions are minimal, making it environmentally acceptable. To date, geothermal power has not been significantly exploited because conventional technologies are constrained to specific geologies, and newer, enhanced geothermal technologies are risky and costly. The workshop was convened to explore whether investment in advanced geothermal technologies might reduce the risk and cost to the point where the U.S. military would be able to take advantage of geothermal power at installations and FOBs.

REPORT ORGANIZATION

The rest of this report is organized as follows:

- In Chapter 2, we summarize the technologies of geothermal energy extraction and describe implications for military use.
- In Chapter 3, we describe ongoing federal support for geothermal energy research and development (R&D).
- In Chapter 4, we report the main technical findings of the workshop, particularly the breakout sessions.
- In Chapter 5, we draw implications and conclusions for DARPA and DoD.

[1] Defense Science Board, *Report of the Defense Science Board on DoD Energy Strategy, "More Fight—Less Fuel,"* Washington, DC, February 2008.

- Several appendixes accompany the text of the report:
  - In Appendix A, we provide estimates of the fully burdened cost of power (FBCP) under varying conditions of conflict intensity and geography.
  - In Appendix B, we provide more extensive descriptions of the workshop breakout sessions and the technical points made.
  - In Appendix C, we summarize the plenary and lightning sessions.
  - In Appendix D, we provide the workshop agenda.

Chapter 2
Geothermal Energy Technology

In this chapter, we summarize the current technology of geothermal energy discovery and extraction. We then describe some implications for military use.

EXPLORATION AND CHARACTERIZATION

The first step in tapping geothermal energy is identifying and characterizing potential geothermal resources. Satellite imagery and aerial photography help to identify areas that potentially hold such resources. Geologists identify features such as seismic faults that have a high probability of containing geothermal resources. They also use published heat flow or other data from wells drilled by the oil and gas and mining industries to identify high probability areas.

After an area has been surveyed, geologists usually perform on-site field analyses of high potential sites. These analyses include geochemistry, geophysical surveys, and electric, magnetic, and seismic tests.

The final step in the exploratory phase is to drill a small-diameter hole—called a temperature gradient hole—to depths of up to 4,000 feet to penetrate the reservoir and provide data such as temperature and pressure. Currently, temperature gradient holes are the only way to identify at-depth temperatures. They can cost as much as a few hundred thousand dollars, but are much cheaper than production wells.

DRILLING

The process of drilling a geothermal well is similar to that for an oil or gas well. However, the peculiarities of geothermal resources, such as deeper wells and harder rock, make drilling geothermal wells challenging and expensive. The cost of drilling can account for 60 percent or more of the total capital investment. Also, the process is inherently risky. Current drilling success rates are around 20 percent. Geothermal power requires at least two wells: an injection well and a production well. To ensure a sufficient flow of hot water to the surface, additional wells may have to be drilled.

Geothermal drillers use oil and gas drilling rigs. These rigs use a rotating drill bit to cut through rock. The drill bit connects to a “drill stem” made up of steel pipes. At the surface, the drill rig rotates both the drill stem and drill bit. Drillers circulate “mud” through the hole to cool the drill bit and remove cuttings. The mud sometimes stops circulating and escapes through the borehole wall.

Geothermal wells are supported by steel or titanium casings cemented to the borehole wall. Casing a geothermal well is expensive, representing a significant portion of total well construction costs.

ENHANCED GEOTHERMAL SYSTEMS

Most of the earth does not have the high temperature geothermal resources, in situ water resources, and porous rock required for conventional geothermal power. Enhanced geothermal systems (EGSs) enable the exploitation of marginal geothermal resources by creating an artificial geothermal reservoir with improved heat transfer.

Reservoirs are created by stimulating existing geologic structures to increase the permeability and porosity of the rock system. Well stimulation is typically done by chemical or mechanical methods. Chemical stimulations inject acidic material, while mechanical methods inject large amounts of highly pressurized water.

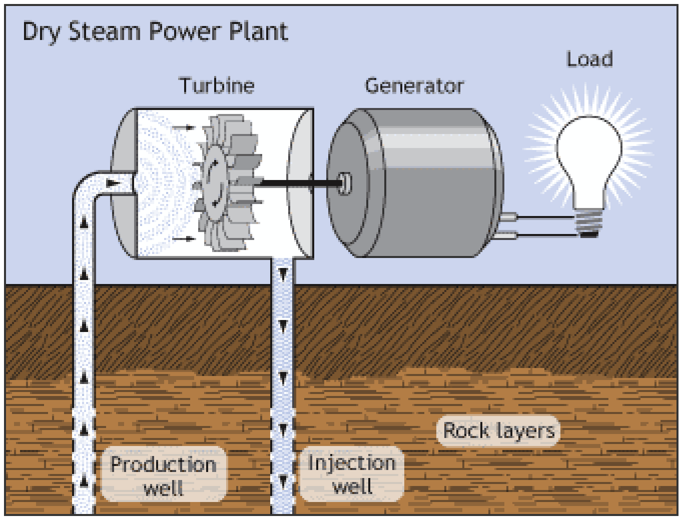
The goal of well stimulation is to create a permeable and porous geothermal field, without short circuits between well holes. Short circuits are fluid paths that travel directly between the injection and production well holes without transferring sufficient heat to be useful at the surface. To reduce the risk of short circuits, large scale EGSs may need multiple wells.

POWER PRODUCTION

Geothermal systems generate power by using the heat to generate steam, which in turn is used to power a Rankine cycle. The Rankine cycle uses steam to spin a turbine, and then condenses the steam and reinjects the water into the well. Although all geothermal power plants use a Rankine cycle, the specific technologies vary depending on the characteristics of the geothermal resource, including temperature and pressure. Geothermal power plants can be divided into three types: dry steam, flash steam, and binary systems.

Dry Steam

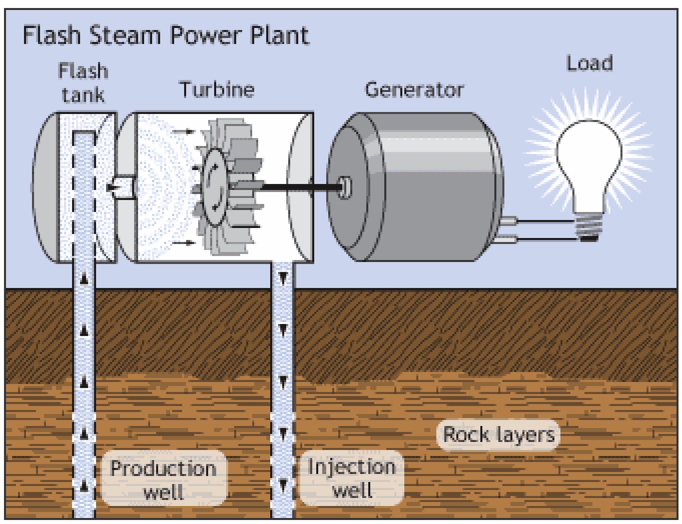
For these plants, the hot, dry steam from a geothermal well directly powers a turbine. They have the simplest design, but have limited applicability because dry steam can only be generated by the hottest geothermal resources.



Source: Europe's Energy Portal, *Geothermal energy,* www.energy.eu/focus/geothermalpower.php.

Flash Steam

Flash steam systems convert hot, pressurized geothermal fluids into steam to generate electricity. The geothermal fluids are "flashed" into steam by reducing their pressure in a flash tank. The resulting steam is used to directly power a turbine. Except for the flash tank, the equipment in a flash steam system is the same as in a dry steam system.

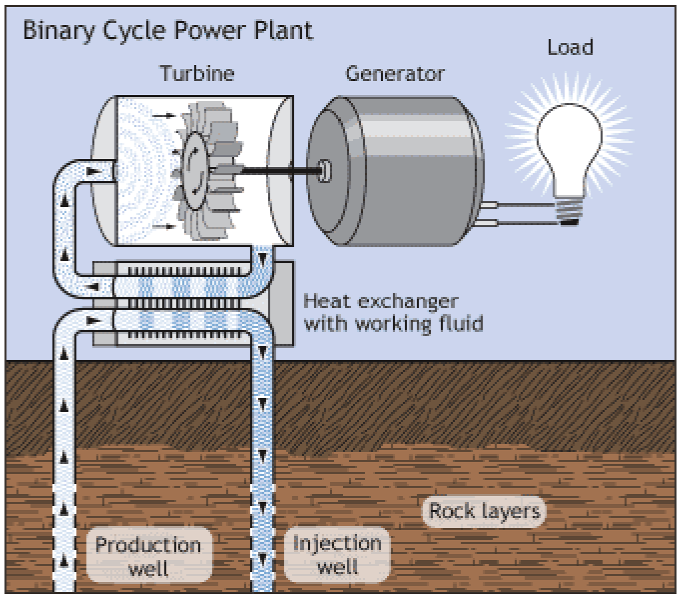


Source: Europe's Energy Portal, *Geothermal energy,* www.energy.eu/focus/geothermalpower.php.

Because they can use lower temperature resources than dry steam plants (above 180 °C), flash steam systems are currently the most widely deployed type of geothermal power plant.

Binary Systems

Binary systems produce power from geothermal fluids with temperatures below the boiling point of water. Binary plants consist of two fluid loops: the geothermal fluid and a working fluid with a low boiling point such as isopentane or isobutene. The geothermal fluid transfers heat to the working fluid through a heat exchanger. Because the working fluid has a lower boiling point, it converts to steam and is used to power the turbine. The working fluid steam is then condensed and again run through the heat exchanger in a closed loop. The geothermal fluids are re-injected into the injection well.



Source: Europe's Energy Portal, *Geothermal energy,* www.energy.eu/focus/geothermalpower.php.

Cooling Systems

Geothermal plants require cooling systems to condense the working steam back into water. Both air and water cooling are used. Water cooling is more efficient due to water's higher specific heat and density. However, this system requires heat to be diverted into a large body of water such as a river or lake. Air-cooled systems operate independent of geographical features, but are less efficient. If ambient air temperature or humidity is high, air cooling requires large fans, increasing both the footprint and parasitic power demands of the cooling system.

Ground Source Heat Pump

A ground source heat pump (GSHP) uses the earth's subsurface temperature to heat or cool a space. GSHPs have three parts: (1) a well, consisting of underground tubing in either horizontal trenches or vertical wells; (2) a working fluid,

generally water, which is pumped through the well; and (3) a heat pump, which extracts thermal energy from the fluid.

Tubing for Horizontal GSHP

Technically, GSHPs are not a source of geothermal energy; more accurately, the ground provides an energy storage system. Unlike geothermal wells, the heat flux into GSHP wells from the environment is small. During the winter, GSHPs extract warm temperature air and inject cooler temperature, gradually cooling the well. In summer the cycle is reversed, extracting cool temperature air from the ground and injecting warmer temperature, warming the well. GSHPs are more efficient than traditional cooling and heating because of the nearly constant temperatures of the geothermal resource. Also, they are relatively inexpensive and can be fairly rapidly installed.

Two types of GSHP wells can be used, depending on the nature of the project. Vertical well systems consist of wells drilled to depths of up to a few hundred feet. These systems are best suited for applications that require significant amounts of space conditioning and a small footprint. Horizontal wells consist of trenches up to 10 feet deep. These wells require a larger footprint and do not provide the cooling capacity of vertical well systems, but are cheaper and quicker to install.

IMPLICATIONS FOR MILITARY USE

Although the technology of geothermal energy is straightforward in some respects, it poses considerable challenge for military use in others. For example, putting geologists on the ground in hostile territory requires defense assets (soldiers, patrol vehicles, and aircraft, for example) to protect them while they work. Bringing a drilling rig onto a site requires transporting that rig to the theater, moving it from place to place, and protecting it while on site. Further, a geothermal production well has prodigious logistics requirements, for drill bits, drill strings, drilling muds, casing material (steel or titanium and cement), and fuel. Trained personnel are also needed to operate and maintain the rig and its attached equipment.

Uncertainty whether a geothermal well will prove successful imposes another challenge. A military commander in the field wants to be certain how energy will be supplied to the location and to be able to count on that supply while there.

Even if successfully deployed, geothermal energy can require considerable time to establish. A single production well can take several weeks to drill, generally more than one well will be needed, and more time will be required to construct a geothermal power plant. An expeditionary force is likely to need a reliable source of energy much more quickly than this.

Finally, geothermal energy might be developed at various locations, but once wells are dug and a power plant constructed at a particular spot, the assets are immobile. This immobility would be unsuitable for an expeditionary force that needed to move from time to time, though a geothermal energy infrastructure left for civilian use could be helpful in achieving broader U.S. political objectives in an area of interest.

These various challenges have several implications:

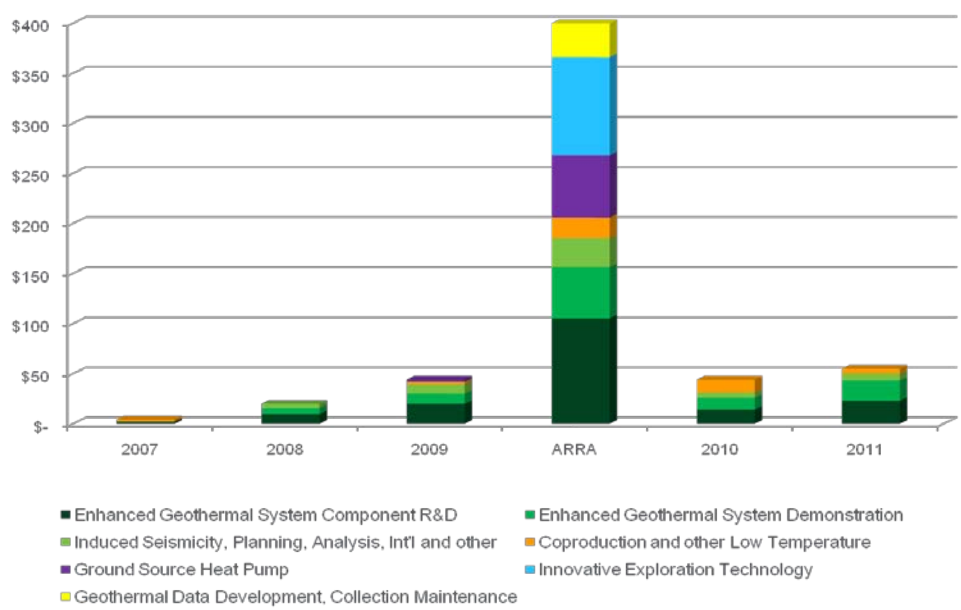
- Current conventional geothermal energy technology probably is unsuitable for U.S. expeditionary forces except where, for one reason or other, they expect to remain for a long period (1 or more years).
- Such technology better applies to fixed installations. Even there, however, it requires a fortuitous combination of available resources at or near an installation. Better information on where geothermal resources are located would be of military value.
- An EGS is more likely to apply to military circumstances because potentially it could be utilized at a wider variety of locations. It requires considerable logistics support, however, and is costly to implement. More advanced technology might help in these respects.
- Ground source geothermal energy appears to apply both to expeditionary forces and fixed installations. The logistics needed to install and maintain it are minimal. However, it does not work well in all soils and provides only heating and cooling, not power, so it could reduce but not eliminate the need for other sources of power.

Chapter 3
Federal Support for Geothermal Energy

DEPARTMENT OF ENERGY

The Department of Energy (DOE) is the primary source of geothermal research funding in the federal government. Over the past few years, geothermal funding has gone from near zero to $40–$50 million per year along with several hundreds of millions of dollars allocated in the American Recovery and Reinvestment Act (ARRA) of 2009. The graph below shows annual funding amounts and ARRA spending on geothermal.

DOE Expenditures on Geothermal Energy



Including ARRA funds, DOE's Geothermal Technology Program (GTP) has supported nearly $900 million in geothermal research, development, and demonstration projects over the past few years, enabling nearly 200 projects. GTP projects encompass a range of technologies, as shown in Table 1.

Table 1. DOE Geothermal Energy Support, by Type of Project ($ million)

Project type	Funding
EGS demonstration projects	198
EGS component R&D	232
Exploration technologies	189
GSHP demonstrations	157
Low temperature resources R&D	56
National geothermal data system	28
Geopressurized resources	15
Coproduced fluids from oil and gas wells	7
Total	882

Many of these geothermal technology investments, if successful, would enhance the value of the technology to DoD. However, DOE's funding is not aimed at military use of the technology, so it may not overcome some of the logistics or other barriers to such use.

DEPARTMENT OF DEFENSE

The Navy Geothermal Program is DoD's primary investor in geothermal energy. The Navy program is administered by its Geothermal Program Office (GPO) at the Navy Air Weapons Station, China Lake, CA. GPO manages the Coso Geothermal Field at China Lake and conducts geothermal exploration and development at other military facilities.

Coso has an installed capacity of 270 MW and has generated more than $400 million in revenue. The monies are used for energy conservation projects and geothermal exploration—looking for further opportunities to develop geothermal power on military installations. GPO has conducted such exploration at several installations, including Naval Air Station Fallon and Hawthorne Army Ammunition Depot, NV, Naval Air Field El Centro, CA, and Marine Corps Air Station Yuma, AZ.

Chapter 4
Challenges and Potential Solutions

In this chapter, we summarize the findings of the workshop regarding technical progress that needs to be made if the U.S. military is to make widespread use of geothermal energy. Our assumptions regarding the use of this energy source by military forces are as follows:

- Alternative sources of energy that can be used in a theater of operations, such as at an FOB, would have high military value if they could substantially reduce the logistics requirements of transporting conventional energy there.
- The ability of such sources to purify water at an FOB would further increase their value because of the high cost of transporting water in theater.
- However, the value of these alternative energy sources in theater would be substantially reduced if they themselves imposed large logistics costs.
- Energy from sources other than the power grid would be valuable at fixed installations because they would reduce reliance on that grid.
- A large renewable energy source on Guam would be timely and valuable because of the planned move of tens of thousands of military personnel there, because the island government is seeking to add renewable energy capacity, and because water purification may one day be needed to augment the island's water supplies.

Workshop discussion was carried out in eight breakout sessions, the main findings of which are summarized here. (Appendix B contains more details.)

Resource Identification and Characterization

Putting geothermal geologists on the ground in a theater to identify resources is costly and dangerous. The technology of remote sensing could reduce the need for on-site geologists, but it needs improvement. Advances in the following remote sensing technologies could help in this regard:

- Gravity gradiometry
- Hyper spectral imagery, such as hyper spectral light detection and ranging (LIDAR)
- Radar-based gas detection

- Infrared surface temperature measurement
- Electromagnetic and thermomagnetic measurement
- Gamma ray spectrometry.

At-depth measurements are the only way to fully understand a geothermal system, but drilling 500-foot temperature gradient holes may be impractical in a conflict area. Automating the drilling process or developing ground-penetrating sensors, with wireless communication capability, that can be dropped from aircraft and would measure such things as temperature, thermal conductivity, humidity, and soil gas composition would help to more rapidly characterize resources.

Workshop participants cited four specific advances needed to overcome technological challenges:

1. Improved sensor performance in terms of depth, sensitivity, and range and improved capability to read sensor output quickly and accurately.
2. Smaller, lighter gravity gradiometers, able to operate at greater heights and capable of better signal-to-noise resolution.
3. Better integration and downsizing of sensors so that various measurements can be done simultaneously from a single overflight.
4. Better use of existing DoD data on the physical characteristics of potential or actual areas of conflict for geothermal exploration.

DRILLING

Discussion centered on what might be done to decrease the time needed for and cost of wells. At present, logistical requirements of geothermal wells probably preclude their application to expeditionary situations. Suggestions included the following:

- Automating the drilling process, at least up to 300 feet in depth
- Installing casing during the drilling process
- Drilling larger diameter holes in order to use coiled tubing, which is easier to deploy and automate
- Application of spallation drilling, using water at high heat and pressure to fracture rock
- Strengthening materials in drill pipe, perhaps through the use of composite materials with greater strength than steel

- Dropping water to produce down-hole power through the use of a down-hole turbine.

ENHANCED GEOTHERMAL SYSTEMS

EGSs must be utilized where the conditions for exploiting natural geothermal energy are deficient in one respect or another (insufficient heat gradient, rock permeability, or fluid access).

Participants suggested techniques to improve rock fracturing, including the insertion of chemicals, gases, or liquids into underground formations, much as is done in oil field recovery programs.

Underground fracture mapping needs further development. Desirable properties include the following:

- Better resolution and accuracy of underground images from seismic monitoring
- Improved capability of microseismic tools to withstand down-hole heat and moisture
- Use of smart tracers and reactive tracers to interrogate the fracture structure at a particular location.

Drilling improvements also could advance EGSs. Suggested improvements include the following:

- More accurate directional drilling and enhanced horizontal drilling capability
- Measurement while drilling by, for example, using wired drill pipe or fiber-optic drill string with the ability to transmit down-hole fracture and heat reservoir information to the surface.

ENERGY CONVERSION

A principal challenge in the conversion process is to improve efficiency. Currently, only about 10 percent of the energy content of geothermal heat is converted into electricity. Also, substantial energy and material are used in the cooling process, especially air cooling. Participants identified several areas for improvement:

- Improved materials in heat exchangers
- Improvements in membrane technology

- Improved motor and fan technology
- Novel working fluids with better heat transfer capabilities
- Thermoelectric active cooling
- Using waste heat more productively, such as for flash distillation of waste water and water purification
- Reinjection of waste heat into the ground.

Geothermal Power System Integration

Few technical issues impede integration of geothermal power into systems providing power to military operations. However, integrating geothermal power with potable water production would be valuable, and avoiding contamination of existing aquifers with geothermal brines is important.

Participants suggested a few technical improvements to better deal with brines:

- Improved methods for cleaning brines to avoid scaling and other tubing deposits
- Improved materials to render geothermal energy equipment more resistant to a variety of brine components.

Ground Source Heat Pumps

The efficiency of a GSHP system depends on the thermal conductivity of the soil and is at a minimum where the ground is entirely dry. Although GSHP technology is relatively straightforward, some ideas for improvement were offered:

- A “magic dust” to add to wells to increase soil conductivity anywhere
- A means to detect soil moisture other than digging a hole, such as dropping a moisture sensor into an area to assess the potential effectiveness of a GSHP system
- The use within a military encampment of water-filled explosive or ballistics protective barriers for heat exchange, perhaps combined with an evaporative cooling system
- The use of wastewater to enhance soil heat conductivity
- The use of GSHPs to cool or warm soldiers directly, for example, in their bivouac sacks, rather than a tent or larger area

- The use of the drill itself as the heat exchanger. This might be done by mounting an augur on the back of an all-terrain vehicle (ATV), drilling into the ground, and circulating a fluid through the augur to accomplish the needed heat exchange.

MILITARY INSTALLATIONS

The United States does not own the geothermal resources at most overseas locations and might have to negotiate for their use with host country governments. On the other hand, geothermal energy development might help with nation building in some instances.

For both overseas and domestic exploitation of geothermal energy near installations, several technological areas for improvement were noted:

- Better mapping of the boundary between the earth's lithosphere (the crust and upper portion of the mantle) and asthenosphere (the hotter and deeper part of the upper mantle)
- Reducing drilling costs through
  - leveraging advances being made in oil and gas drilling,
  - advanced hybrid drilling technology, or
  - advanced acoustic refraction and seismic techniques to better define geothermal resources before drilling
- Developing means to exploit heat from ductile rocks
- Improving heat pipe technology, possibly through improved chemical reactions and catalysts.

GUAM

On Guam, the main challenge is finding out whether geologic conditions are favorable to the development of geothermal energy. An exploratory well to gather data on the island's geothermal heat gradient is required to address this problem.

Such a well would pose few technical challenges. A drilling rig used for water wells would be capable of drilling the necessary exploration well, at a cost of a few hundred thousand dollars. However, exploitation of geothermal resources would require a much bigger drilling rig, at a much higher cost. Because of the logistical challenges of moving equipment and suppliers to Guam, establishing geothermal power there could cost as much as $5–$6 million per MW, assuming the natural resource is present.

Participants gave several reasons why the use of geothermal power on Guam would make good sense from a military perspective:

- The upcoming military personnel relocation eventually will strain the existing power grid, so that a new power source will be needed.
- DoD seeks to become less reliant on the grid to power its installations, and geothermal energy offers a possible means to do so on Guam.
- Successful exploitation of geothermal energy on the island could provide sufficient power to desalinate seawater and augment the island's water supplies, thus avoiding the need to drill 22 new water wells and putting less pressure on the existing aquifer.
- Successful demonstration of geothermal energy on Guam might lead to its application at other island locations that lie near volcanic activity.

Another option is to extract energy from hydrothermal vents in the general vicinity of Guam, some of which lie at the tops of undersea mountains. However, formidable technical challenges would have to be overcome to successfully tap this energy:

- Stronger undersea cables to transmit power at ocean depths (around 13,000 feet) in the vicinity of Guam
- Automated production of power at the bottom of the sea
- Drilling at a depth of more than 13,000 feet from a submersible rig.

These challenges probably would take many years to overcome. Any advances in technology could prove valuable around the world, but the problem on Guam is relatively short-term in that military personnel will be moving there in the near future. For now, an exploratory well would seem the more applicable course of action.

Chapter 5
Implications and Conclusions

The use of geothermal energy has many potential benefits for military operations. It could provide a base load source of power both for expeditionary forces and fixed installations. For expeditionary forces, geothermal could potentially reduce the high costs and logistical requirements of power. For fixed installations, geothermal could reduce dependence on the grid and vulnerability to grid disruption. In both cases, geothermal power generation could enable water purification.

Supplying geothermal energy to expeditionary forces poses several challenges. Standard exploratory techniques involve putting geologists on the ground and digging exploratory wells. Where geothermal shows high potential, production wells must be dug and power plants erected. Geothermal power plants and the required cooling towers take up considerable space. The process of exploration, drilling, and power plant construction may require several months and considerable logistics support. The logistics and time associated with geothermal power are formidable barriers to DoD use.

Long-term advances in geothermal technology could ease some of the cost, time, and logistical challenges. Remote sensing might obviate the need for geologists on the ground. Automated and hybrid drilling might reduce the logistics and time needed to drill wells. Better fracture mapping and fluid qualities could help reduce the uncertainty of drilling and heat transfer capabilities. More productive ways to use waste heat would reduce the need for cooling towers and increase the efficiency of the power production process. Any of these advances also would help in applying geothermal energy to civilian use.

Advances in EGSs could be of substantial military value because they would broaden the geographic application of geothermal energy. Workshop participants identified a number of technological challenges and outlined possible solutions. Over the longer term, investment in EGSs might be the best use of DoD funds devoted to geothermal energy technology. In the short run, however, DOE already is investing nearly $400 million in EGS R&D, and awaiting the results of this research may be prudent before investing further.

GSHP technology may have immediate application to both expeditionary missions and fixed installations. This technology has the advantage of being quick to install and presenting few logistical challenges, even in an expeditionary environment. Although technical advances may provide some benefit to this technology, a more basic need appears to be demonstrations under varying conditions to see whether it can be practically applied and is cost-effective.

In the short run, geothermal energy could be of high military value in Guam. Significant advances in undersea energy extraction would be needed if this type of energy, perhaps tapped from thermal vents, were to be brought to Guam via undersea cable. On Guam itself, however, the more pressing need is to investigate the heat gradient of the island subsurface and the potential for geothermal energy by drilling a temperature gradient well. For a number of reasons (enumerated in this report), DoD investment in such investigation would appear to have significant payoff.

DARPA is not presently investing in geothermal technology. The results of the workshop indicate that this form of energy holds promise for military use under a variety of circumstances. Widespread application poses technological challenges, many of which were identified at the workshop. The most relevant from a DoD perspective likely are the advancement of EGS, particularly through improvements in sensor and automation technologies, and means to increase the efficiency of geothermal power production while decreasing its footprint. Other, more immediate applications for military purposes, such as GSHPs and geothermal power on Guam, appear to be more matters of investigation and assessment than of technical progress, though advances in the technologies associated with these applications certainly would be helpful and render them more attractive than otherwise.

Appendix A
Fully Burdened Cost of Power

The FBCP is the total cost of supplying power to U.S. armed forces wherever located. For an FOB, which usually obtains power from generators, for example, it is the total cost of transporting and operating the generators, including capital and maintenance costs, personnel, fuel, and backup power. In such an instance, the cost of fuel itself is a fully burdened cost, meaning the entire cost of delivering the fuel to the location of the generators has been included. This cost includes the cost of military assets used to protect fuel truck convoys or other methods of delivering fuel, as well as attrition of fuel, personnel, and equipment during the effort [see "Fully Burdened Cost of Fuel" (FBCF) below].

The FBCF is relevant to DARPA's investigation of geothermal power because it indicates what it costs to supply power by conventional means (generators burning JP-8) and hence the cost challenge geothermal power must meet to be a cost-effective alternative. For example, if it costs $2/kWh to supply power to an FOB by conventional means, then geothermal energy would be cost-effective if it can be supplied on a timely basis at a lesser cost.

For purposes of this study, we are interested in the FBCP under several different circumstances. For an FOB, we want to know the cost under peacetime and low- and medium-intensity wartime conditions, as exemplified by operations in Bosnia, Iraq, and Afghanistan, respectively. The peacetime costs of supplying power overseas assume the conditions of an FOB, namely that generators are used. The main difference between peacetime and low- or medium-intensity operations is the cost of the defense assets used to protect fuel supply lines from enemy interdiction, and the attrition of fuel, personnel, and equipment during the process.

We also want to know the FBCP in Guam because of DARPA's interest in the potential for geothermal power there. This cost is likely lower than that of supplying an FOB.

The following sections describe the elements of the FBCP and analyze how these costs vary by military circumstances. Generally, the FBCF makes up the largest component of cost, but other elements are important as well.

FBCP ELEMENTS

Our model for estimating the FBCP expressed in terms of dollars per kilowatt hour is as follows:

$$\$/\mathrm{kWh} = \frac{D + M + F + S + T + B}{\mathrm{kW} \times \mathrm{H}},$$

where D = capital depreciation,

M = maintenance and repair,

F = fuel,

S = support personnel,

T = transport of personnel and equipment,

B = backup power source,

kW = kilowatts, and

H = hours.

In our base case, we assume a 1-year period, with an average operating rate for a generator. The U.S. Army's *Tactical Electric Power Operational Requirements Document* specifies that a tactical generator in an operational setting is expected to operate 4,080 hours per year.[1]

FOBs use a range of generator sizes and combinations of generators. To illustrate a range of costs for power at an FOB, we calculate the FBCP for a 60 kW and a 5 kW generator. These costs are calculated for military generators, though sometimes nonmilitary versions are substituted in the field, and their costs, including maintenance and repair (M&R), can differ from those shown here.

Capital Cost

A 60 kW generator set (genset) requires a trailer and a backup power source, so the acquisition cost actually is that of a 60 kW power plant, which is two 60 kW gensets mounted on a combined trailer. As of FY10, the cost of a 60 kW power plant is \$86,636. A tactical genset is expected to last 15 years, and we amortize the capital cost over that period, so the annual depreciation cost is \$5,776.

A 5 kW genset generally is carried on the back of a truck or mounted on a trailer pulled by a High Mobility Multipurpose Wheeled Vehicle (HMMWV). For

[1] U.S. Army Training and Doctrine Command (TRADOC), *Tactical Electric Power Operational Requirements Document* (TEP ORD), CARDS 16126, Appendix G, August 18, 2004.

present purposes, we assume the latter, which makes it a 5 kW power unit. The cost of such a unit is $21,698. Again, we assume a 15-year lifetime for this equipment, so that the annual depreciation cost is $1,446.

Maintenance and Repair

In 2002, the project manager—Mobile Electric Power commissioned a comprehensive study of the M&R costs of tactical quiet generators, including the generator sizes under consideration here.[2] Labor costs were calculated for an Army Specialist 4, and parts costs came directly from purchase invoices. We extrapolated the labor rates to 2010 by updating the rate for an Army Specialist 4 and adjusted the parts costs with an index for gensets that is part of the Producer Price Index published by the Bureau of Labor Statistics (BLS).[3] Also, we assumed that even in peacetime a genset operating at an FOB would operate 4,080 hours per year. Given this assumption and the adjustments, the annual cost of maintenance for a single 60 kW genset in 2010 is $2,815 and for a power plant, therefore, $5,630. The annual cost for a 5 kW power unit in 2010 is $2,345. These costs cover both parts and labor but exclude indirect personnel support associated with the labor such as cooks, administrators, chaplains, and the like.

Support Personnel

The costs of genset mechanics already are included in the M&R costs provided above. Below we allocate a certain number of hours to truck driver costs. For these, we take the fully loaded hourly rate of an Army E-4, which in FY10 is $33/hour.

Transport

TRANSPORT TO THEATER

Transport costs include both transport to a theater of operations and within it. The prime mover of a 60 kW power plant, probably a 2½-ton truck, may be brought to a theater for other purposes, in which case its cost to move the genset is negligible. On the other hand, if it is brought to a theater primarily to move the genset, its cost should properly be included as part of the cost of power there, and any other capacity it has is simply an added benefit. For our purposes, truck costs are considered part of the cost of supplying power overseas. In this section, we examine the cost of transporting a 60 kW power plant or a 5 kW genset to a theater. We separately calculate the cost of moving a truck as well.

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[2] Modern Technologies Corporation, *Advanced Mobile Medium Power Sources Business Case Analysis*, June 2002.

[3] U.S. Department of Labor, BLS, Producer Price Index for manufactured turbines and turbine generator sets, pcu333611333611.

Transport to a theater can be by air or sea. Transport by air is more expensive, but the time needed to position equipment is much less. According to the U.S. Transportation Command (USTRANSCOM), rates for the movement of equipment to the Iraqi theater from the East Coast are as follows:

- By channel air: $2.87/lb
- By sea: $1.44/lb.[4]

A 60 kW power plant weighs 13,440 lb. Thus, the cost of moving such a plant to a theater such as Iraq or Afghanistan would be $38,573 by air and $19,354 by sea. These costs would double if transport back to the United States were included. However, to fully assess them, we would need to estimate the length of time of an engagement. If it were only 1 year, then the transport cost would be the numbers shown doubled for transport back to the United States, but if it were say 10 years, the amortized annual cost would be a 1/10th of those costs. For purposes of assessment, we assume a 5-year overseas engagement, with equipment supplied by air and returned by sea. In this case, the cost of transporting a 60 kW power plant would be $38,573 + $19,354 = $57,927 in total, or $11,585 per year.

We make similar calculations for a 5 kW power unit, which weighs 2,320 lb. The cost of transport for such a unit over a 5-year engagement would be $2,000 per year.

Transport within Theater by Truck

The acquisition cost of an M1078 Light Medium Tactical Vehicle, a 4×4, 2½-ton truck used to haul a 60 kW power plant, is approximately $165,000, and such a truck is expected to last for 20 years. According to the Program Management Office, Medium Tactical Vehicles (PMO MTV), a 2½-ton truck travels 2,252 miles per year in contingency operations and 1,779 miles per year during peacetime. We assume the truck averages 20 mph and charge driver labor costs at the rate of an E-4 for 20 percent of his total time.[5] The 2½-ton truck averages about 8 miles per gallon (mpg) under stop-and-go conditions, so it uses about 222 gallons per year in peacetime and 282 gallons per year in low- or medium-intensity warfare. According to PMO MTV, the M&R costs for a 2½-ton truck were $1.35 per mile during wartime and $1.14 per mile in peacetime in FY08. We update these cost numbers to 2010 using the gross domestic product (GDP) deflator, so that for our purposes they are $1.38 and $1.16. Finally, a 2½-ton truck weighs 16,499 lb and an equipped driver 400 lb,[6] so transport to a theater such as Iraq and back by air

[4] Communication from the Military Surface Deployment and Distribution Command Fusion Center, USTRANSCOM, February 28, 2008.

[5] Truck mechanic costs are included in M&R rates. We assume that the drivers have other duties when not moving a generator since only a few hours per week are devoted to that task.

[6] Air Force Pamphlet 10-1403, *Air Mobility Planning Factors*, December 18, 2003. The driver weight factor includes body armor, weapon, ammunition, clothing, and food. We allocate 20 percent of the cost of transport of the driver to this mission.

and sea would be $71,456, which for a 5-year scenario would average $14,291 per year. Table A-1 shows the combination of these costs.

Table A-1. Annual Costs of 2½-Ton Truck ($)

Cost category	Peacetime	Low-intensity	Medium-intensity
Depreciation	8,250	8,250	8,250
M&R	2,028	3,040	3,040
Transport to and from theater	14,291	14,291	14,291
Fuel	1,388	4,360	5,361
Driver cost	13,728	13,728	13,728
Total	39,685	43,669	44,670

Thus, the total annual cost of a 2½-ton truck in theater would be $39,685 under peacetime conditions overseas and would range between $43,669 and $44,670, depending on the intensity of warfare.

We calculate similar numbers for an M998 HMMWV (Table A-2), which costs about $50,000, and we assume a 20-year lifetime. We assume it travels the same distances in peacetime and during conflict as the M1078. A HMMWV gets around 10 mpg, so it uses 178 gallons per year during peacetime and 225 gallons per year in low- or medium-intensity conflict. According to TRADOC, the operating cost for a HMMWV in 2007 was $1.71 per mile. We update that number to 2010 using the GDP deflator, resulting in $1.79/mile. The present model of the M998 weighs 7,700 lb, and a fully equipped driver, 400 lb. Given this, the costs of transport to and from a theater amortized over 5 years would be $6,706.[7]

Table A-2. Annual Costs of a HMMWV ($)

Cost category	Peacetime	Low-intensity	Medium-intensity
Depreciation	2,500	2,500	2,500
M&R	3,184	4,031	4,031
Transport to and from theater	6,706	6,706	6,706
Fuel	1,112	3,478	4,277
Driver cost	13,728	13,728	13,728
Total	27,230	30,443	31,242

Fuel

As stated above, the cost of fuel to the military is a fully burdened cost. Its magnitude varies by how far it must be transported and the conditions of that transport,

[7] Again, we allocate only 20 percent of the cost of driver transport to and from the theater to power production.

but in all cases it includes the military infrastructure necessary to deliver it to its destination. (The final section of this appendix discusses the FBCF and estimates its magnitude.) For an FOB operating under peacetime, low-intensity, or medium-intensity conditions, estimated FBCFs are as follows:

- Peacetime: $6.25/gal
- Low-intensity: $15.55/gal
- Medium-intensity: $19.10/gal.[8]

A 60 kW genset uses 4.51 gallons per hour, so if it operates 4,080 hours annually in an operating theater (including one at peace), it uses 18,401 gallons in a year. Thus, the annual costs of fuel for such a generator are as follows:

- Peacetime: $115,005
- Low-intensity: $286,136
- Medium-intensity: $351,459.

A 5 kW genset uses 0.57 gallons per hour, so it uses 2,326 gallons per year, and its annual costs of fuel are as follows:

- Peacetime: $14,535
- Low-intensity: $36,169
- Medium-intensity: $44,426.

Backup Power

For the 60 kW genset, this cost is covered under the acquisition cost of a power plant since it already has two generators that are available to back each other up. For the 5 kW unit, this cost is more difficult to assign. Sometimes no backup is available, and soldiers can be without power for a time until a generator is fixed. On other occasions, extending power distribution equipment from another generator or even from a power-exporting vehicle may be possible, at least temporarily. We assign no specific cost to the backup for a 5 kW power unit, but note that being without an external power source, even for short periods, can significantly reduce military effectiveness.

[8] See “Fully Burdened Cost of Fuel” later in this appendix for how these numbers were derived. They include the costs of protective assets and attrition.

Kilowatt Hours

We assume a 60 kW or 5 kW genset operates 4,080 hours in theater, so that the annual power outputs are 60 × 4,080 = 244,800 kWh and 5 × 4,080 = 20,400 kWh, respectively.

Summary

Tables A-3 and A-4 summarize the various cost elements we have identified for the 60 kW and 5 kW gensets.

Table A-3. Annualized FBCP for 60 kW Power Plant ($)

Cost category	Peacetime	Low-intensity	Medium-intensity
Depreciation	5,776	5,776	5,776
M&R	5,630	5,630	5,630
Transport to and from theater	11,585	11,585	11,585
Transport within theater by truck	39,685	43,669	44,670
Fuel	115,005	286,136	351,459
Total cost	177,681	352,796	419,120

Table A-3. Annualized FBCP for 5 kW Power Unit ($)

Cost category	Peacetime	Low-intensity	Medium-intensity
Depreciation	1,446	1,446	1,446
M&R	2,345	2,345	2,345
Transport to & from theater	2,000	2,000	2,000
Transport within theater by truck	27,230	30,443	31,242
Fuel	14,535	36,169	44,426
Total cost	47,556	72,403	81,459

Dividing total costs by the amount of power generated, first for a 60 kW power plant, we get the following:

- Peacetime: $0.73/kWh
- Low-intensity warfare: $1.44/kWh
- Medium-intensity warfare: $1.71/kWh.

For a 5 kW power unit, we get the following:

- Peacetime: $2.33/kWh
- Low-intensity warfare: $3.55/kWh
- Medium-intensity warfare: $3.99/kWh.

Summarizing, our ranges of fully burdened power costs at an FOB over genset sizes 5 kW–60 kW for the three operating conditions are as follows:

- Peacetime: $0.73/kWh–$2.33/kWh
- Low-intensity warfare: $1.44/kWh–$3.55/kWh
- Medium-intensity warfare: $1.71/kWh–$3.99/kWh.

From this analysis, the comparative cost of power will depend directly on the scale of alternative sources examined. Costs for relatively small sources such as a 5 kW power unit are relatively high, whereas those from larger units, such as a 60 kW power plant, are lower. An FOB that uses mainly large gensets, even some larger than the 60 kW versions, likely would be at the lower end of the scale, whereas one with many distributed power sources would be at the upper end.

The cost of power also depends upon the state of warfare. The cost of power from a 60 kW genset more than doubles in a medium-intensity scenario compared with peacetime, while that of a 5 kW genset rises by 71 percent.

One other point is evident. The FBCF is a principal driver of the FBCP, and larger generators use less fuel per kilowatt hour than smaller ones. For FOBs, geothermal energy probably would compete best where it replaced distributed power sources, through either centralized power production with distribution equipment or ground source methods applied directly at those sources.

GUAM

Direct Cost of Power

Guam is an island located in the North Pacific Ocean, three-quarters of the way from Hawaii to the Philippines, lying at the southernmost tip of the Northern Marianas Islands. It has a tropical marine climate that is warm and humid with relatively little temperature variation. The island has both a rainy and a dry season and is subject to periodic typhoons.

The U.S. military plans to shift some 20,000–25,000 Marines and dependents from the Japanese island of Okinawa to Guam over the next several years. Another 10,000 support personnel are expected to move as well. For this reason, the

military has an interest in alternative means of meeting the increase in energy demand this will generate.

At present, Guam meets nearly all of its energy needs with petroleum products shipped in by tanker. The Guam Power Authority and three independent power producers operate petroleum-fired power plants totaling 550 MW of capacity.

In 2008, Guam enacted legislation to compel the island's utilities to provide increasing percentages of renewable energy over the next 25 years. The schedule is as follows:

- 5 percent of net electricity sales by December 31, 2015
- 8 percent by December 31, 2020
- 10 percent by December 31, 2025
- 15 percent by December 31, 2030
- 25 percent by December 31, 2035.

The direct cost of electricity for a large power user (one whose demand exceeds 200 kW per day) on Guam is $0.09303/kWh.[9] This would be the cost of power to the armed forces if they relied solely on civilian transport of fuel to the island and on the island's electrical grid.

Fully Burdened Cost of Power

What if U.S. forces were forced to rely on their own means of supplying fuel to Guam for purposes of generating power? In that case, the cost of military assets used to deliver the fuel would be relevant.

The Naval Air Systems Command (NAVAIR) has made initial attempts to estimate such costs.[10] The analysis examined the fully burdened cost of delivering fuel to land-based aircraft using airborne tankers, a way Guam's military forces might be supplied with fuel were the military itself required to supply it. The analysis did not include assets to protect the tankers from enemy interdiction. It estimated that, with a Defense Energy Support Center (DESC) standard fuel price of $2.86 per gallon, the fully burdened cost of delivered fuel would be $14.15 per gallon. If fuel delivered to Guam by civilian ocean tanker otherwise would have cost $2.86 per gallon, the increment in fuel cost is $11.29 per gallon. In such a case, fuel would become by far the most important cost component of power to

[9] Guam Chamber of Commerce, "Cost of Doing Business on Guam," rates as of December 2009. The rate quoted is at the margin for a large user.

[10] "Fully Burdened Cost of Fuel for Aviation/Fuels," Presentation for Navy-Hosted Fully Burdened Cost of Fuel Meeting, NAVAIR Cost Department, October 15, 2009.

the military on Guam, and the cost likely would at least quadruple, to $0.40/kWh.[11]

Freeing Military Installations from Grid

A 2008 Defense Science Board study examined U.S. military reliance on commercial electric grids and concluded the following:

> Almost complete dependence of military installations on a fragile and vulnerable commercial power grid and other critical national infrastructure places critical military and Homeland defense missions at an unacceptably high risk of extended disruption.[12]

It recommended that the military "reduce the risk at fixed installations from loss of commercial power and other critical national infrastructure."[13]

One means suggested was to "island" U.S. military facilities to the extent practicable, meaning to produce as much power as economically feasible on or near the installation from alternative sources such as renewable fuels, and to seek means to increase energy efficiency.

When viewed in this way, the relevant cost of alternatives to geothermal is that of producing it from sources such as wind, solar, or mini-nuclear power plants. Guam has ample wind resources, but periodic typhoons probably limit the amount that can be usefully constructed. The cost of photovoltaic power on a cents/kWh basis varies with the amount of available sunshine and type of installation, but is estimated to range between $0.25/kWh and $0.40/kWh in most direct uses. Concentrated solar might provide a less expensive option, but would require considerable land area and may not be a practicable alternative in this particular setting.

Conclusions

The direct cost of power on Guam at present is only about $0.093 per kWh for a large user. However, the island has mandated the use of increasing proportions of renewable energy, which probably will drive costs up. Further, the fully burdened cost of delivering power on Guam is higher, perhaps as much as $0.40 per kWh. Also, the military has been admonished to reduce its reliance on the grid by producing power from alternative sources and increasing its energy efficiency. These alternative sources presently are likely to cost upwards of $0.20 per kWh, and maybe as much as $0.40 per kWh. Hence, if geothermal power can be produced

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[11] The exact amount would depend on the number of hours that military generators ran, their fuel use rate, and their capital and operating costs. A quadrupling of overall power cost probably is a reasonable estimate of the cost increment. On the other hand, the Navy might supply Guam through seaborne rather than airborne tanker. We do not have an estimate of the FBCP for this mode of fuel supply, but suspect it would be quite a bit less than that for airborne supply.

[12] See Note 1, Chapter 1, p. 3.

[13] See Note 1, Chapter 1, p. 6.

on Guam or brought to the island from nearby at costs in this range, it may prove a competitive alternative.

FULLY BURDENED COST OF FUEL

Tables A-3 and A-4 suggest that the FBCF is a major component of the FBCP and indeed dominates the FBCP for a 60 kW power plant, so understanding the FBCF concept—and the reasons why the numbers are of that magnitude—is important.

In 2001, the Defense Science Board (DSB) released a report that said that the cost of fuel to military users was much higher than simply the purchase cost.[14] The report pointed out that an entire logistics network exists to move fuel from where it is purchased to the frontlines where it is consumed. Some of the costs of this network are reflected in the standard price of fuel (the price charged by DESC to the services), but many of the costs are not included, particularly those incurred by the services themselves in moving fuel from where they receive it from DESC to the front. The DSB report also said that the military services maintain fuel logistics networks in peacetime as well as wartime, so that the cost of fuel even in peacetime is higher than the purchase price. The report pointed out that the delivered cost of fuel might be anywhere from four or five times the purchase price to as many as a hundred times or more depending on how far the fuel must travel and what logistics were involved in transporting it.

A second DSB report issued in 2008 reiterated these findings and suggested that DoD has been slow to recognize the implications, namely that defense fuel consumption is far more costly than credited, so that cost-effective alternatives for reducing demand are being systematically ignored.[15] The report also emphasized that military effectiveness is directly related to the cost of fuel because part of that cost is the defense assets used to protect fuel convoys, which are diverted from other activities.

British analysts, too, have recognized that the cost of fuel to the military is greater than the purchase price. A February 2009 report issued by the Royal United Services Institute asserted that 7 liters of fuel are used to get 1 liter to the front, and that the FBCF is as much as 40 times the purchase cost.[16]

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[14] Defense Science Board Task Force on Improving Fuel Efficiency of Weapons Platforms, *More Capable Warfighting Through Reduced Fuel Burden*, Washington, DC, January 2001.

[15] See Note 1, Chapter 1.

[16] Royal United Services Institute, “Alternative Energy and Sustainability in the Military 2009,” p. 1, www.rusi.org/downloads/assets/Alternative_Energy_and_Sustainability_Conference_Report_-_FINAL.pdf.

Because of these reports and concern expressed by commanders in the field,[17] DoD has become more focused on the FBCF and has taken steps to incorporate it into defense planning. In April 2007, the Under Secretary of Defense for Acquisition, Technology and Logistics, USD(AT&L), signed a memo making it DoD policy to incorporate the FBCF into tradeoff analyses involving fuel using end items with an eye toward making them more energy efficient. USD(AT&L) further requested that each of the services analyze the FBCF for a particular weapon system. Some of the numbers reported below are a result of the effort to provide such numbers for the Joint Light Tactical Vehicle.

FBCF Estimates

In 2007, the DoD Planning, Analysis and Evaluation (PA&E) office developed a method for estimating the FBCF, which it applied to delivery of fuel at domestic sites and abroad. The method first was applied at domestic installations, and an average taken of the costs at several such installations. These costs included the direct purchase cost of fuel, pertinent delivery equipment, and dedicated personnel. This yielded an estimated cost of $5.61/gallon for JP-8, with the underlying standard price of fuel equaling $2.30/gallon at the time. The present standard price of fuel for JP-8 is $2.82/gallon, so if other costs had remained the same that factor alone would have increased the estimate to $6.13/gallon. Even if these other costs rose no more than the general rate of inflation in the economy, the result in today's dollars would be $6.27/gallon.

PA&E worked with the Institute for Defense Analyses to produce FBCF estimates in a theater of operations, taking into account the defense assets used there to protect fuel convoys. The resulting estimates were $7.50/gallon for low-intensity warfare, $11.80/gallon for medium-intensity, and $19.00/gallon for high-intensity, based on a standard price of $2.10/gallon at the time. Adjusting for the increase in this price since then, these numbers would now be $8.22/gallon, $12.52/gallon, and $19.72/gallon, respectively.

A similar approach was taken by the Energy Security Group (ESG), which used actual data for specific military units in theater to estimate the FBCF for fuel going into Iraq and Afghanistan. The use of in-the-field data gives these estimates a stronger basis than the theater estimates noted above. The numbers were $13.80/gallon in Iraq and $17.16/gallon in Afghanistan.[18] At that time, the standard price of fuel was $1.66/gallon. Assuming that standard price was included in the estimate, then adjusting for the change in standard price since that time, those prices now would be $14.96/gallon and $18.32/gallon, respectively.

[17] Marine Corps Major General Richard Zilmer stated these concerns bluntly in requesting means to reduce fuel dependency in the field. He said "without [a] solution, [convoy] personnel loss rates are likely to continue at their current rate. Continued casualty accumulation exhibits potential to jeopardize mission success."

[18] Cited in a presentation by Dave Hull and Marti Roper, Office of the Deputy Assistant Secretary of the Army—Cost and Economics (ODASA-CE), "Fully Burdened Cost of Fuel: Changes to the AOA Process," DoD Cost Assessment Symposium, February 2009.

Even more recent estimates were provided at a Military Operations Research Society workshop in November, 2009.[19] A Marine Corps analysis of the FBCF in Afghanistan took two different approaches (shown as ranges in Table A-5) to estimation and derived similar numbers for each of three fuel delivery scenarios. The numbers are quite close to those for fuel delivery in low- or medium-intensity conditions derived by ESG.

Table A-5. FBCF for Delivery to FOB in Afghanistan (35 Miles from Base Camp)

Delivery method	FBCF ($/gallon)
Convoy delivery/security	9.20–11.81
Convoy delivery/air security	15.63–18.59
Air delivery/security	28.94–30.78

Adjustment for Attrition

The method developed to estimate the FBCF fully accounts for the assets used to move fuel from where it is purchased to the ultimate consumption point and for military assets used to protect that transport. However, it does not take into account attrition of fuel, equipment, and personnel. Some fuel purchased does not reach the frontlines, and in low- or medium-intensity battle conditions, some trucks are damaged or destroyed and personnel injured or killed. These factors suggest that the FBCF is higher than shown above.

Adjustment to Standard Price of Fuel

DESC includes a small factor to account for fuel attrition in its Standard Price of Fuel. In establishing this factor, DESC recognizes that there are evaporation and combat losses, but it applies the factor equally worldwide because its policy is to price fuel equally everywhere in the world. Thus, if costs of attrition are higher in some locations than others, the differences are not reflected in differential prices to customers.

We can reasonably assume that fuel attrition would be greater in combat zones than elsewhere. Thus, there is good reason to believe that DESC's standard price understates the true cost to the organization of delivering fuel to such zones while slightly overstating costs elsewhere.

Existing data are consistent with the contention. In 2008, DESC informed Congress that it was adjusting its standard price to cover 1 million barrels (42 million gallons) lost in Iraq and Afghanistan in that year. The DESC *Fact Book FY08* reveals that the organization delivered 883 million gallons into those two theaters in

[19] Edward Blankenship and Randal Cole, "Fuel and Water for OEF: Towards Developing 'Fully Burdened Costs,'" Presented at Military Operations Research Society Energy Workshop, November 30, 2009.

FY08. Thus, there was about a 4.5 percent attrition rate on DESC-delivered fuel into Iraq and Afghanistan that year. However, worldwide in 2008, DESC delivered 132.5 million barrels of fuel, so that Operations Iraqi Freedom (OIF) and Enduring Freedom (OEF) attrition accounted for only 0.75 percent. Losses elsewhere about doubled that figure, so that the worldwide attrition rate was about 1.5 percent. From this, the standard price of fuel understated the true cost of fuel by about 3 percent in Iraq and Afghanistan. Applying this 3 percent factor to DESC's current standard price for JP-8 of $2.82/gallon, in-theater delivery costs are about $0.08/gallon greater than the standard price. At the same time, delivery costs elsewhere are about $0.02/gallon lower.

Despite the use of military assets to protect fuel deliveries, some fuel losses also are suffered in delivering it from the point at which DESC turns it over to forces in the field. Below we estimate losses of 100 fuel trucks per year in low-intensity warfare and 200 per year in medium-intensity. Some of these may have occurred after the trucks had unloaded part or all of their fuel, and some may have been included in DESC's fuel attrition costs. However, to understand the potential magnitude of further fuel losses, we assume an average of 2,000 gallons of remaining fuel in trucks that were destroyed and that this fuel is not included in the DESC numbers. In that case, the total fuel lost would be 200,000 and 400,000 gallons in low- and medium-intensity warfare, respectively. Below, we note that according to the DESC *Fact Book FY08*, 139 million gallons were delivered into Afghanistan in 2007 and 533 million gallons into Iraq. Thus, the above-calculated fuel losses are fairly negligible, 0.04 of 1 percent in Iraq and 0.7 of 1 percent in Afghanistan. Because of the uncertainty surrounding these estimates and their relatively small magnitudes, we ignore them for present purposes.

ADJUSTMENT FOR LOSSES OF PERSONNEL AND EQUIPMENT

Combat-related destruction of trucks or other equipment and injury or death of fuel-delivery personnel are direct costs of fuel delivery in combat zones. As noted above, these costs generally are not included in estimates of the FBCF. Their estimation requires knowing how much such destruction takes place and attaching unit costs.

A recent Army Environmental Policy Institute (AEPI) report provides information on casualty factors for fuel convoys in Iraq and Afghanistan in 2007.[20] It estimates that there were 132 fuel-convoy-related casualties in Iraq and 38 in Afghanistan in that year, and that rates of such casualties (casualties per fuel convoy) were 0.024 in Iraq and 0.042 in Afghanistan. The casualties include deaths and injuries to soldiers and civilians engaged in delivering fuel to consuming units and FOBs.

[20] Army Environmental Policy Institute, *Sustain the Mission Project: Casualty Factors for Fuel and Water Resupply Convoys*, September 2009.

The costs of such casualties can be roughly calculated in terms of foregone earnings and hence productivity loss.[21] The fully loaded wage of an E-4 is $60,000. If the casualty means either that the person was killed or sufficiently injured to prevent ever working again, the net present value of lost product over 40 years (a soldier's expected working life) discounted at 4 percent is about $1,187,000. According to the AEPI report, there were 270 fuel delivery-related casualties in FY07 in Iraq and Afghanistan. If each resulted in a death or long-term disability, the lost product was about $320 million. Probably the number was somewhat less because some of the injuries did not fully disable the soldiers involved. On the other hand, there would have been associated medical expenditures to treat injuries, some of these lasting for many years. For present purposes, we assume these two factors balance each other out. According to DESC, in FY07, 672 million gallons of fuel were delivered to OIF and OEF. Dividing this number into $320 million, the FBCF in a low- or medium-intensity conflict should be increased by about $0.48/gallon to reflect casualty losses.

Most fuel in a combat zone is delivered by truck, and scattered evidence indicates that truck losses in Iraq and Afghanistan have been extensive. However, the data are not as readily available as that for human casualties. We briefly review these data and then roughly estimate an annual cost for truck losses.

Time magazine reported in October 2009 that during June to September, 123 vehicles bringing supplies to NATO troops were destroyed in Afghanistan. If 50 percent of those were carrying fuel, that would be 61.5 vehicles within 3 months, or a rate of 246 per year.

In March 2009, the Government Accountability Office (GAO) cited DoD in reporting that in June 2008, 44 trucks and 220,000 gallons of fuel were lost due to attacks or other events while delivering fuel to Bagram Air Field in Afghanistan.[22] Although a good deal of fuel was delivered to Bagram, it was not the only destination within the country at that time so that other trucks may have been destroyed elsewhere during the same month. Even so, such a rate of truck loss would translate to more than 500 trucks per year.

The Royal United Services Institute, a British organization, reported that its forces had suffered the loss of 89 fuel tankers since 2006.[23] The report doesn't specify a location, but presumably includes both Iraq and Afghanistan. Although this number is considerably smaller than those cited above, the British constitute only a small fraction of total forces in either Iraq or Afghanistan.

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[21] Literature on the value of human life and injury is extensive, including estimates based on people's expenditures to avoid risk. These values are higher than those calculated here, but their derivation is somewhat controversial, and we do not wish to engage in that debate in this report.

[22] GAO, "Increased Attention on Fuel Demand Management at DoD's Forward-Deployed Locations Could Reduce Operational Risks and Costs," Statement of William M. Solis before the Subcommittee on Readiness, Committee on Armed Services, House of Representatives, March 3, 2009.

[23] See Note 16, this appendix, p. 1.

Finally, for historical perspective, a U.S. military report written in 1995 about the Soviet-Afghan War stated that the Soviets lost 11,389 trucks in that country between December 1979 and February 1989.[24] If 50 percent of those were carrying fuel, the Soviets lost almost 5,700 fuel trucks over 9+ years, or about 630 trucks per year.

The unit cost of military fuel trucks varies by type and size of vehicle. A new M978 Heavy Expanded Mobility Tactical Truck (HEMTT) can cost a few hundreds of thousands of dollars, and transporting it to a theater involves additional costs. Other military fuel trucks cost less and will have depreciated some due to age and condition. Nevertheless, one can conservatively estimate that the cost to deliver a fuel truck capable of carrying 2,500 or 5,000 gallons into Iraq or Afghanistan would be upwards of $150,000. If we conservatively estimate further that 100 fuel-carrying trucks per year are lost in a low-intensity theater such as Iraq and 200 per year in a medium-intensity theater such as Afghanistan, the aggregate annual cost would be $15 million and $30 million, respectively. As noted above, according to the DESC *Fact Book FY08*, 139 million gallons of fuel were delivered into Afghanistan in FY07 and 533 million gallons into Iraq. Combining the various loss, cost, and gallonage estimates, the FBCF should be increased by $0.03/gallon in a low-intensity conflict and by $0.22/gallon in medium-intensity. These numbers are very rough, but clearly the cost of truck losses is part of the cost of delivering fuel, and the adjustment does not seem unreasonable.

Summary

We now summarize the above adjustments made to the FBCF. Our starting point is the PA&E estimate of the peacetime cost at a domestic installation and the ESG estimates for low- and medium-intensity conflicts in Iraq and Afghanistan.

Table A-6. Adjustments to FBCF ($/gallon)

Adjustment	Peacetime	Low-intensity	Medium-intensity
Initial cost	5.61	13.80	17.16
Higher DESC Standard Price for JP-8	+0.52	+1.16	+1.16
Other cost inflation	+0.14	—	—
Uniform Standard Price	–0.02	+0.08	+0.08
In-theater casualties	—	+0.48	+0.48
Truck losses	—	+0.03	+0.22
Adjusted FBCF	6.25	15.55	19.10

[24] Lester Grau, “Convoy Escort in Guerrilla Country: The Soviet Experience.” *Military Police*, Winter 1995.

Appendix B
Breakout Sessions

Session A—Resource Characterization

If the military is to successfully exploit geothermal energy, there must be technology to rapidly and accurately identify resource potential (underground heat, fluid, and permeability) in the field. Instruments that can detect and measure surface faults, heat, and gases would help in this regard.

With present technology, geologists usually must physically explore potential sites to determine whether it is worth drilling gradient wells and eventually whether to drill potential production wells. In theater, such exploration often will be impractical if not impossible. Remote sensing from the air appears to be a possible alternative.

Several means to improve image resolution were suggested. These included use of hyper spectral imagery such as hyper spectral LIDAR, radar-based gas detection, infrared surface temperature measurement, electromagnetic and thermomagnetic measurement, and gamma ray spectrometry. Although these technologies exist, they either have not been employed for geothermal exploration or are not sufficiently advanced as yet to be of practical use. Generally, the geothermal industry is characterized by smaller firms that do not spend much on R&D.

Gravity gradiometry also was suggested as a means to improve image resolution. Gradiometry is similar to gravimetry, but is able to measure the gravity gradients of an underground object in multiple dimensions. Gravity gradiometry is conducted from the air but is sensitive to the height and speed of the aircraft involved. Further, the imagery that results can be difficult to interpret because of the sheer quantity of data obtained and a low signal-to-noise ratio. The military in theater probably can fly low to the ground at a controlled speed to improve data acquisition and resolution, though this may subject an aircraft to enemy threat.

Although remote sensing gives clues about geothermal resources, at-depth measurements are the only way to fully understand a geothermal system. However, drilling 500-foot temperature gradient holes may be impractical in a conflict area. Automating the drilling process or developing ground-penetrating sensors, with wireless communication capability, that can be dropped from aircraft and would measure such things as temperature, thermal conductivity, humidity, and soil gas composition would help to more rapidly characterize resources.

Session participants cited four specific advances needed to overcome technological challenges. First, we need improved sensor performance in terms of range,

sensitivity, and coverage. We also need improved capability to read sensor output quickly and accurately.

Second, gradiometers need to be made smaller and lighter (they each weigh several hundred pounds), able to operate at greater heights, and capable of better signal-to-noise detection. To be wholly effective for geothermal energy resource identification, this technology requires an order of magnitude improvement from where it stands today.

Third, sensors need to be better integrated with one another so that various measurements can be done simultaneously from a single overflight. At present, various sensors detect and measure at different distances and perspectives, complicating the data-gathering process. Reductions in the sizes of the various detection instruments also would increase their military utility.

And fourth, current DoD data on the physical characteristics of conflict areas should be integrated and used for geothermal exploration. DoD has detailed physical data, including LIDAR and satellite imagery, of conflict areas in which it operates. Utilization of this data would reduce the need for new geothermal exploration.

Although most of the technological challenges are not DoD specific, the military might especially benefit from an improved capability to detect geothermal potential when it is planning where to locate FOBs. It also has the advantage of few limitations on the ability of its aircraft to explore close to the ground. If logistics challenges associated with geothermal drilling and power conversion can be overcome, advances in geothermal detection technology could prove of considerable military value.

Session B—Drilling

Geothermal resources involve the drilling of exploratory holes to determine temperature gradient and production holes through which to draw the geothermal resource. An exploratory well can be drilled from a rig carried on the back of a flatbed truck. Such wells are small in diameter, need not go deeper than a few hundred feet, and are relatively inexpensive. The drilling technology for these wells is well developed.

Production wells, however, must be larger in diameter and may be drilled to depths of several thousand feet. The technology of drilling strongly resembles that of oil and gas drilling, which uses rotary drill bits, drill pipe, and cement casing. Such wells impose prodigious logistics requirements and can be exceedingly costly to drill. For example, a participant who owns a drilling company estimated that the drilling of a production well requires 3–4 trucks of fuel per kilometer (0.6 mile) of depth plus very large quantities of cement. Such a well also requires considerable time because drill bits have to be drawn up through the hole and replaced, pipe extended, etc., and unscheduled maintenance issues often arise. This

same participant estimated that drilling averages about 30 feet per hour and that it takes about 15 days to drill 1 kilometer (0.6 mile).

Discussion centered on what might be done to decrease the time needed and cost of wells. One suggestion was to automate the drilling process, at least up to 300 feet in depth. Another was to put in casing while a well is being drilled. Currently, drilling ceases while casing is sealed. And yet another was to drill larger holes in order to use coiled tubing, which is easier to deploy and automate.

The wearing out and replacement of drill bits was another focus. One participant asked whether rotary drill bits even would be used if drilling technology were being invented today. An option would be spallation drilling, in which water at high heat and pressure is used to fracture rock. Spallation also can be combined with ordinary rotary drilling to make up a hybrid drilling system. Such a hybrid probably would cut the time needed to drill and reduce drill bit wear, but would require energy to heat water and a source of water as well.

Yet another useful technological advance would be a material strengthening of drill pipe. Steel pipe under stress at high temperatures tends to break down, but it may be possible to construct composites that would improve pipe performance.

Another idea was to use falling water to produce power down-hole. Power would be scavenged in the drilling process by moving water down and through a turbine located at the bottom of the hole.

These challenges are formidable and probably would require years of R&D to overcome. Few appear unique to the military application of geothermal power; rather, their solutions would help in geothermal power use for all applications. The military might gain from the advances, but DARPA might better focus on technological advances that directly apply to DoD needs.

SESSION C—ENHANCED GEOTHERMAL SYSTEMS

Geothermal energy depends on a relatively strong underground heat gradient, reservoir rock permeability, and fluid access. An EGS becomes necessary when at least one of these is lacking. For example, an EGS might take the form of better fracturing of reservoir rock to make the underlying heat bed more accessible. It also might involve use of superior heat transfer mechanisms to water or brine.

Techniques to improve rock fracturing received considerable attention at the workshop. These included insertion of chemicals, gases, or liquids into underground formations, much as is done in oil field recovery programs. A difference is that oil deposits generally are located in porous rock, whereas geothermal resources tend to be located in harder rock systems.

Explosives also can be used for this purpose and have the advantage that the military is familiar with their capacity and use. However, precisely controlling the

results of underground fracturing explosions is difficult, and this technique has not proven effective in the past.

Participants also stressed that underground fracture mapping needs further development. In particular, underground images from seismic monitoring require better resolution and more accuracy. Microseismic tools provide useful information for reservoir modeling, but that information could be considerably improved if the tools could withstand down-hole heat and moisture. Smart tracers also could be used to interrogate the fracture structure at a particular location. The technique involves injecting a tracer material into a fracture and following the path it takes. Reactive tracers work via the same principle but allow for the tracer material to interact with other materials within the fracture and use the information obtained to more accurately characterize the nature of the fracture.

The payoff to accurate underground mapping appears significant. Sometimes the difference between the success and failure of a production well is a matter of only a short distance, as little as several feet in some cases.

Participants also examined drilling improvements within EGSs. More accurate directional drilling and enhanced horizontal drilling capability would improve EGS prospects. Also, as is done in the oil industry, measuring while drilling should be possible by, for example, using wired drill pipe or fiber-optic drill string with the ability to transmit down-hole fracture and heat reservoir information to the surface.

From a military perspective, EGSs offer a means to extend the application of geothermal energy to a wider set of circumstances. This could be particularly valuable in the field, where alternative means of providing power are expensive and sometimes dangerous. However, the potential technological improvements outlined by participants do not seem unique to military applications. Further, DOE already is supporting nearly $400 million in EGS technology development. Given these facts, awaiting the results of the research may be prudent before deciding whether to commit new DoD funds.

SESSION D—ENERGY CONVERSION

Geothermal heat is converted to power by bringing it to the surface and using it in the form of steam to drive a turbine, which in turn drives a generator. The steam is then recondensed and the water reused. A technology known as the organic Rankine cycle (ORC) is used in most modern geothermal power plants.

A principal challenge in this process is to make it more efficient. Currently, only about 10 percent of the energy content of the heat is converted into electricity. Further, a good deal of energy and material are used in the cooling process, especially in air cooling.

Session participants suggested a number of improvements:

- Improved materials in heat exchangers
- Improvements in membrane technology
- Improved motor and fan technology
- Novel working fluids with better heat transfer capabilities
- Thermoelectric active cooling
- Using waste heat more productively, such as for flash distillation of wastewater and water purification
- Reinjection of waste heat into the ground.

Military use of heat-to-power conversion technology would depend in part on conditions on the ground. Deploying the ORC process in a desert environment would be difficult because of the high daytime heat. On the other hand, the technology could be well suited for a cold climate as that would ease the heat dissipation issue and reduce the need for multiple cooling towers. Time would be needed, materials would have to be transported to build a plant, and security-related issues could arise, particularly in protecting any cooling towers needed because of the space they require.

Overall, widespread military use of geothermal power plants might be better suited to fixed installations than expeditionary forces. On the other hand, FOBs that nominally were intended for temporary use sometimes have remained operational for years. In addition, a geothermal power plant could be turned over for native civilian use once its military application ended. Such a "leave behind" could have value in sustaining civilian operations and providing a continuing U.S. contribution towards a country's future welfare.

Session E—Ground Source Heating and Cooling

Strictly speaking, ground source heating and cooling is not a form of geothermal energy. Rather, the ground is used as an energy storage source in the sense that temperate air is used to facilitate cooling or heating by heat pumps. Nevertheless, the workshop investigated this energy technology because it may apply to FOBs and installations and because technological progress might have a civilian as well as a military payoff.

GSHPs were installed at some 4,000 living units at Fort Polk, LA, beginning in 1994 under a 20-year energy service performance contract. The project was part of a broader energy savings effort, which resulted in about a 33 percent average

electricity savings and 40 percent peak savings.[1] The technology has not been applied in a theater, however.

Application of the technology is straightforward. A trench or hole is needed to lay piping to conduct heat exchange, and the piping needs to be connected to a distribution system to where cooling or heating is needed. Depending on the underground temperature gradient, a trench will need to be 3 to 10 feet in depth and can be dug fairly quickly by a Bobcat or other earth-moving equipment, even a small drilling rig carried on the back of a HMMWV or ATV. Alternatively, since the Force Provider system is placed on a 3-foot gravel pad, the piping could be laid first and gravel placed on top.

The efficiency of a GSHP system depends upon the thermal conductivity of the soil, which is at its least where the ground is entirely dry. Dry sand, for example, has a thermal conductivity that is only about 30 percent that of wet sand. Bentonite grout increases soil conductivity, but generally the qualities of a specific soil determine what best enhances conductivity. Innovation is needed to find a “magic dust” to increase conductivity anywhere.

In addition, a means is needed for detecting soil moisture other than digging a hole, such as dropping a penetrating moisture sensor into an area to assess where best to establish a GSHP system. Technical advance is needed to make such a sensor a reality.

An option at a military encampment would be to use water-filled explosive or ballistics protective barriers for heat exchange. These might be combined with an evaporative cooling system. Also, wastewater could be used to moisten soil at an encampment to enhance heat conductivity.

Another idea that surfaced was to cool the soldier rather than a tent or larger area. With this approach, a GSHP system would be connected to individual bivouac sacks.

Yet another idea was to use the drill itself as the heat exchanger. A drill bit or augur might be mounted on the back of an ATV, drilled into the ground to a depth of 10 feet or so, and circulated with water or some other fluid. A single drill might suffice for one soldier, but multiple drills could be injected to cool or heat a tent or building. Such a system might offer portability as well: when soldiers are ready to move, the drills could be pulled back up.

The consensus was that the technological barriers to military use of GSHPs are few and they may well prove worthwhile in an FOB context. Some equipment would be needed to establish such a system (over what already should be present), and ongoing logistics are minimal. The use of GSHPs should be tried on an experimental basis to determine their practicality in an FOB environment and the

[1] J. A. Shonder, P. J. Hughes, R. A. Gordon, and T. M. Giffin, *Geothermal Heat Pump ESPC at Ft. Polk: Lessons Learned*, Oak Ridge National Laboratory, July 1997.

energy savings likely to result. If such experiments prove successful, military doctrine could be altered to accommodate more widespread use.

Session F—Geothermal Power System Integration

Geothermal energy power involves several forms of system integration:

- Integrating geothermal power with other forms of power generation, particularly other renewable sources
- Integrating geothermal power generation with production of potable water and avoiding contamination of existing aquifers with geothermal brine
- Integrating geothermal with oil and gas production to utilize hot water produced in those operations
- Integrating geothermal power production into expeditionary military operations.

The first of these was not considered a problem. Geothermal energy provides a base load source of power that can be easily integrated into grid dispatch operations. Moreover, if geothermal power can be produced, the rationale for other renewables is unclear. Solar and wind power offer possible interim solutions until geothermal power comes on line or when it fails to meet demand, but the latter seems unlikely for a forward operation, where solar and wind likely would add only small amounts of power. Geothermal power requires a backup source, however. A geothermal power plant will be on line 98 percent of the time, but it requires a small amount of downtime for scheduled and unscheduled maintenance.

The connection between geothermal energy and fresh water is twofold. On the one hand, purification of waters produced from a geothermal energy project could be useful for military purposes because the delivery of fresh water to the front is very costly. If daytime power demand is high relative to supply, this could be done at night. Also, it is important that a water purification process not reduce overall water temperature or pressure.

Brines from geothermal projects tend to be caustic and corrosive. Better technology is needed to clean these brines to avoid scaling and other tubing deposits. Alternatively, tubing materials might be improved to make them more resistant to a variety of brine components.

Segregating brines produced in geothermal operations from freshwater aquifers is important. This can be accomplished through proper well casing and identifying aquifer locations before drilling takes place.

Integration of geothermal energy with water from oil and gas producing operations makes sense but is not a military imperative. In one of the plenary sessions, a DOE representative indicated that department is investing resources to advance technology in this field.

Integration of geothermal power production into military operations poses a number of logistical challenges. For example, in Kandahar province, Afghanistan, 30 Marines and two Harriers reportedly were used to protect a small group of geologists from the U.S. Geological Survey who were operating on the ground. Technological innovation is needed to "do away with geologists," that is, explore geothermal resources entirely by air or from other remote locations.

It also was pointed out that geothermal power plant cooling towers require considerable space, rendering them vulnerable in a theater. The private sector is looking for ways to cool produced brines more efficiently, but the technology is still quite rudimentary. Today, if geothermal power is sited for military purposes, the space to cool will need to be considered.

SESSION G—GUAM

Geothermal Potential

The military is interested in the development of geothermal energy on Guam because 20,000–25,000 military personnel and 10,000 others are scheduled to relocate to the island from Okinawa. The present population of Guam is only about 175,000, so the influx represents a large increment that will strain the existing power grid, which runs entirely on petroleum products, and the island's water supplies.

Guam lies at the southernmost tip of the northern Mariana islands, a part of Micronesia. It is 138 miles south of Saipan, the most populous of the Marianas, and of a series of other islands where there is active volcanic activity. Between Guam and Saipan lie Rota and Tinian, neither of which displays volcanic activity.

A team from Southern Methodist University (SMU) has investigated the Marianas and believes Pagan, an uninhabited island that shows evidence of hydrothermal circulation (hot springs), may have an estimated 50–125 MW of geothermal potential.

The SMU team also believes Saipan—where a well drilled to 125 meters suggests a possible heat gradient of 50–60 °C per kilometer (0.6 mile)—may have geothermal potential, but a deeper well would need to be drilled to confirm this.

Guam has a similar tectonic structure to Saipan and so may offer a similar heat gradient. However, no well has been drilled below the water table on Guam, so no direct empirical evidence supports this conjecture.

Drilling on Guam presents certain challenges, but the breakout group thought them manageable. Most of the population lives on the northern part of the island, which is hilly and has a soil covering and which holds the island's aquifers, which have been tapped at a depth of around 400 feet, most if not all of it above sea level. The southern part is mostly made up of volcanic material. A large portion of the southern half, perhaps one-third, is owned by the U.S. Navy. Because the population is likely to resist drilling that might jeopardize existing aquifers, the breakout group proposed that any drilling be done in the south, with well casing to ensure that drilling fluids are well contained. A well drilled to a sufficient depth anywhere on the island would suffice to determine the heat gradient there.

Such a well poses few technical challenges. A drilling rig used for water wells would suffice for the purpose, and the well probably could be drilled for a few hundred thousand dollars. However, exploitation of geothermal resources would require a much bigger drilling rig, at a much higher cost. Because of the logistical challenges of moving equipment and suppliers to Guam, it could cost an estimated $5–$6 million per MW to establish geothermal power on the island, assuming the natural resource is there.

Despite the lack of a direct technical challenge to exploiting geothermal energy on Guam, the breakout group thought that a strong case exists for DARPA involvement. First, the military personnel relocation will strain the existing power grid, so that some new power source is needed. Second, DoD seeks to become less reliant on the grid to power its installations, and geothermal energy offers a possible means to do so on Guam. Third, successful exploitation of geothermal energy on the island could provide sufficient power to desalinate seawater and thus augment the island's water supplies. This would solve another problem, since 22 new water wells are planned to accommodate the newly arriving military personnel. And fourth, a successful demonstration of geothermal energy on Guam might lead to application at other island locations that lie near volcanic activity.

Hydrothermal Vents

Hydrothermal vents lie in the general vicinity of Guam, some at the tops of undersea mountains. The closest of these is about 40 miles to the west, and other, deeper undersea vents potentially could be sources of energy supply. The problem is to tap them and to transport the power to where people can use it.

The breakout group identified several formidable technical challenges to tapping this source of energy. For one thing, technology today allows the laying of undersea cable to depths of only about 6,500 feet, whereas ocean depth in the vicinity of Guam is about 13,000 feet. Stronger undersea cables therefore would be required to transmit undersea energy from one place to another in this vicinity.

A second challenge would be to produce power at the bottom of the sea. Undersea power production at these depths would have to be entirely automated, a technology not yet developed.

Finally, the deepest drilling today is at ocean depths of 7,000–8,000 feet. This drilling is done from the surface, with a drilling rig on a platform built to withstand heavy weather and other tensions. To drill at 13,000 feet, a submersible drilling rig probably would be required. The technology to do this does not exist today.

The breakout group identified these as long-term technical challenges that an entity like DARPA might find of interest. Although the military could use these technologies, their principal applications would appear to be in civilian use.

Session H—U.S. and Worldwide Military Installations

This breakout session addressed how best to exploit geothermal resources at U.S. military installations worldwide. It was pointed out that the United States does not own the geothermal resources at most overseas locations and might have to negotiate for their use with host country governments. On the other hand, geothermal energy development might assist the United States with nation building at some locations.

Better mapping of the boundary between the earth's lithosphere (the crust and upper portion of the mantle) and the asthenosphere (the hotter and deeper part of the upper mantle) is needed to establish where geothermal energy might be usefully exploited. This boundary, known as the Moho discontinuity, is characterized by a changing chemical composition that provides clues as to where geothermal energy is located.

The cost of geothermal energy extraction also needs to be reduced. Currently, it costs about $4 million per MW installed in the United States and more than that in many overseas locations. About 10 percent is expended on exploration, 25–30 percent on drilling to define the resource base, and 60–65 percent on infrastructure. Several means of reducing cost through technical advance were suggested:

- Leverage exploration and drilling advances being made in oil and gas
- Advance hybrid drilling technology
- Advance acoustic refraction and seismic techniques to better define geothermal resources before drilling.

Another topic was how to exploit heat from ductile rocks, those at temperatures in excess of 350 °C. Some of these can be reached through conventional drilling techniques and exhibit temperatures of 400–500 °C. However, they too would have to be mapped and often exist without accompanying fluid resources.

Finally, the session focused on heat pipe technology. Heat pipes transfer heat between surfaces, with the objective of losing as little as possible in the transition. Improved chemical reactions and catalysts were suggested as two means whereby geothermal energy, if it existed at or near a U.S. military installation, might be practically exploited.

Although the technical advances discussed in this session would facilitate geothermal energy use at U.S. military installations, they do not appear uniquely aimed at facilitating such use. Rather, they would expedite the use of geothermal energy throughout the society and hence might be better supported from the civilian side.

Appendix C
Plenary and Lightning Sessions

Plenary Speakers

Barbara McQuiston—DARPA

Barbara McQuiston described DARPA's efforts in the energy area, pointing out that it has been investing in a wide variety of energy technologies, including advanced biofuels, high-efficiency solar cells, and nano-structured materials. To date, however, DARPA has not invested in geothermal energy technology. She posed a question for the group: "Can you create an ideal engine for turning heat into electricity … that accessing at any depth is free?"

T.C. Moore—DARPA

T.C. Moore described his experience as leader of a U.S. Marine Corps team that recently investigated the realities of energy supply on the ground in Afghanistan. His team looked at how fuel is used by a Marine Expeditionary Force, finding that power generation consumes about one-third of total fuel in the field. He estimated that it costs more than $10/gallon to bring fuel to the frontlines in Afghanistan and water costs almost $5/gallon. These two commodities impose acute logistical challenges. Moore's team concluded that development of alternative sources of energy and of water would be of high military value.

Michael Canes—LMI

The presentation by Dr. Canes focused on the costs of producing power at the frontlines. He provided estimates of these costs under varying conflict conditions, ranging from peacetime in a foreign setting such as Bosnia to low- or medium-intensity operations in places such as Iraq or Afghanistan (see Appendix A). He showed that the costs of supplying power from a 5 kW generator could be as high as $4.00/kWh in a medium-intensity conflict and as high as $1.70/kWh from a 60 kW generator in such a conflict. He also spoke of the cost of power on Guam. Currently, a large user there can secure power for a little more than $0.09/kWh, but the full costs of supplying the island under conflict conditions would be considerably higher, perhaps as much as $0.40/kWh.

David Blackwell—SMU

Professor Blackwell provided a survey of worldwide geothermal resources and of activity to convert these resources into usable energy. He pointed out that in

addition to U.S. efforts, primarily in the western states of California and Nevada, Europe and Australia have tapped geothermal resources and have active programs to expand. He indicated that the opportunities to tap geothermal energy along the U.S. Gulf Coast are considerable. He explained that heat flow from underground sources at a given point is related to tectonic forces and radioactivity properties of the earth's crust at that point. Some worldwide geothermal sources have been mapped, but the data are sparse and much remains to be done to pull these data together and enhance them.

William Tayler and Andy Sabin—U.S. Navy

William Tayler described some of the energy challenges faced by the Navy and the goals it has set. He enumerated challenges that geothermal energy would have to overcome to be useful for a Marine FOB. Andy Sabin described ongoing Navy efforts to exploit geothermal resources in the United States, including programs at China Lake, CA, and Fallon and Hawthorne, NV. He said other locations offer good potential and that the Navy is likely to execute further geothermal exploration and development programs in the Nevada and California areas.

Tim Reinhardt—DOE

Tim Reinhardt described the DOE's geothermal program, including its near-term and longer-term goals. He reviewed the funding history of the program, which fell to nearly zero in FY07 but which has been enormously expanded by the ARRA. The act is putting almost $400 million into geothermal programs over 2 years, while DOE's annual geothermal budget has climbed to more than $40 million. He said that almost $100 million has been invested to date in advanced geothermal exploration techniques and in strengthening the National Geothermal Database. He spoke as well on EGSs, coproduced waters with oil and gas, and GSHPs. DOE's goals include having a fully refined resource assessment done by the U.S. Geological Survey by 2012, developing an EGS system capable of producing and sustaining 5 MW over 5 years from 2015 to 2020, and reaching 30 GW of geothermal energy capacity by 2030.

Lightning Sessions

Phil Rawlings—Trison Construction, Inc.

Phil Rawlings presented information on GSHP systems. He said a vertical installation requires about 400 square feet of ground space, a horizontal installation about 1,200 square feet. A GSHP system can be installed by two people with a small trench-digging machine carried on a flatbed truck working for about 1 week. Rawlings provided data indicating such a system can reduce heat pump power demand by as much as 50 percent and asserted that such a system will not degrade much if any over time. He reported that the effectiveness of ground source geothermal power depends in part on soil moisture content: the moister the

soil is, the higher the effectiveness. At present, his company cannot detect soil moisture without opening up a hole to test it.

Mike Ronzello—Pratt and Whitney Power Systems (United Technologies Corp.)

The Pratt and Whitney (P&W) power system converts heat to power using the ORC. This is a binary cycle system, in which hot water is run through a heat exchanger and vaporized into steam to run a turbine. The vapor is recondensed into water, and the water is reused. Mr. Ronzello reported that the system has an availability factor of 98 percent, counting both unscheduled and scheduled maintenance. It can be installed in 2–3 days and comes in modular 250 kW increments. Stringing together as many as 50 is possible, yielding total power in the 10–12 MW range. The system also requires cooling, which in an air-cooled system takes the form of cooling towers with large fans. P&W is working to improve water recovery in such a way as to produce pure water in its next-generation systems.

Jared Potter—Potter Drilling Company

Jared Potter said that drilling costs are the long oar in the boat regarding geothermal energy. Potter Drilling is working on a hybrid thermomechanical system using thermal spallation as a means to reduce these costs. The idea is to use superheated water to soften and fracture rock, and then drill through the rock using conventional methods. The ultimate objective is to drill into hard rock without having to periodically remove and replace drill bits, thus saving time and money. If completely successful, it would reduce the cost of securing geothermal energy to that of coal. A drawback is that this method is more energy intensive than mechanical drilling. Potter thinks that limestone offers a good candidate for the process because mechanical drilling does not work very well in such rock. So far, thermal spallation has been performed in a laboratory setting but needs to be tested in the field.

Brigette Martini—Ormat Technologies, Inc.

Ormat is a vertically integrated geothermal company, from exploration to power production. It builds turnkey systems for others, but also currently operates over 500 MW of geothermal power systems of its own. Ms. Martini noted that Ormat's exploration aims are to locate heat, underground fluid, and rock permeability. The company does geologic mapping and modeling, LIDAR, other hydro-spectral imaging, chemical analysis, geophysics, and combinations of these techniques. Ormat has conducted geothermal exploration on military aircraft, executing thermal exploration, magnetic and electromagnetic signature, and LIDAR in combination. Ormat is seeking technological improvement in locating better drill-site targets and in reducing drag friction in pipelines to transport fluids more efficiently.

S. Bruce Kohrn—Lockheed Martin

Lockheed Martin has developed a technology called gravity gradiometry, which applies to geothermal energy. Mr. Kohrn said that the technology measures the gravity gradient of a given mass in several dimensions instead of just vertically, thus providing a richer data set concerning material density at the site. The data can be used to analyze fault systems and basement structure. It looks at edge effects, which can be useful in discovering faults and in mapping a magma chamber. The system when deployed on a platform allows quicker access to a site than one that depends on ground access and has fewer problems with physically reaching the site. It could be deployed on a helicopter, which would go over the site more slowly than a fixed wing aircraft and also could be taken much nearer to the ground. It is now an unclassified system and is being deployed commercially. Lockheed Martin is working to improve the resolution of the images obtained from gravity gradiometry and would like to test it at different heights to see the difference that would make in the quality of data obtained.

Appendix D
Workshop Agenda

DARPA sponsored a workshop March 23–25, 2010, at LMI headquarters in McLean, VA, to discuss challenges to military application of geothermal energy. The pages that follow show the workshop agenda.

GEOTHERMAL POWER FOR DOD OPERATIONS

A Workshop Sponsored by the Defense Advanced Research Projects Agency (DARPA)

McLean, VA
23 - 25 March 2010

AGENDA

Location: *LMI, 2000 Corporate Ridge, McLean, VA 22102*

Focus: *Technological Advance Required to Enable the U.S. Military to Exploit Geothermal Energy at Forward Operating Bases (FOBs) and Installations*

Tuesday, March 23

Time	Topic	Presenter
6:00 pm	**Dinner and Welcoming - Opening Remarks**	*Welcome*: Jinendra Ranka (DARPA) *Opening Remarks*: Barbara McQuiston (DARPA)
7:00 pm	**DoD Strategic and Tactical Energy Challenges** • *Strategic energy security concerns* • *Operations at FOBs and installations* ○ *Power systems* ○ *Logistics*	*Speaker*: T.C. Moore (DARPA)
8:00 pm	Adjourn	

Wednesday, March 24

Time	Topic	Presenter
8:00 am	Continental Breakfast	
8:30 am	**PLENARY SESSION 1: The Fully Burdened Cost of Power (FBCP)** • *FBCP in Theater Under Varying Threat Levels* • *FBCP at DoD Installations, including Guam*	*Speaker*: Mike Canes (LMI)
9:15 am	**PLENARY SESSION 2: Global Geothermal Resources** • *Worldwide known and estimated geothermal resources* • *Geological formations, heat gradients,* in situ *water*	*Speaker*: David Blackwell (SMU)
10:00 am	Break	
10:15 am	**PLENARY SESSION 3: Challenges to Military use of Geothermal Power** • *Conventional geothermal systems* • *Constraints at FOBs and installations* • *Barriers to deployment at FOBs and installations*	*Speaker*: William Tayler (USN) Andy Sabin (USN)

GEOTHERMAL POWER FOR DOD OPERATIONS

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AGENDA

Wednesday, March 24 *(Continued)*

Time	Topic	Presenter
11:00 am	**PLENARY SESSION 4: DoE Geothermal** • *DoE Enhanced Geothermal Systems, Status Report* • *Low Temperature Geothermal, Overview and Status Report*	*Speaker:* Tim Reinhardt (DoE)
11:45 pm	**Networking Lunch**	
12:15 pm	**Lightning Presentations**	

	BREAKOUT SESSIONS A AND B	
Time	**Topic A**	**Topic B**
12:45 pm	**Resource identification & characterization** *- How to identify resources quickly and accurately in the field?* Valerie Browning, MCC2	**Drilling** *- How to dramatically increase the speed of drilling?* *- How to reduce logistical needs of drilling?* Doug Blankenship, MCC3
2:30 pm	Break	

	BREAKOUT SESSIONS C AND D	
Time	**Topic C**	**Topic D**
2:45 pm	**Enhanced Geothermal Systems (EGS)** *- How to quickly and accurately stimulate wells at FOBs?* *- How to reduce working fluid losses?* Doug Blankenship, MCC2	**Energy Conversion** *- How to speed the construction and reduce the size of power plants?* Valerie Browning, MCC3
4:15 pm	**Break**	
4:30 pm	**Review of Breakout Sessions**	
5:30 pm	**Adjourn**	

GEOTHERMAL POWER FOR DOD OPERATIONS

A Workshop Sponsored by the Defense Advanced Research Projects Agency (DARPA)

McLean, VA
23 - 25 March 2010

AGENDA

Thursday, March 25

8:00 am	Continental Breakfast	
8:30 am	**Lightning Presentations**	
	BREAKOUT SESSIONS E AND F	
Time	**Topic E**	**Topic F**
9:00 am	**Ground Source Heating and Cooling (GSHC)** - *Why has GSHC not been widely deployed?* Doug Blankenship, MCC2	**Geothermal Power System Integration** - *What are synergies and challenges in using geothermal with other resources and the grid?* Valerie Browning, MCC3
10:30 am	Break	
	BREAKOUT SESSIONS G AND H	
Time	**Topic G**	**Topic H**
10:45 am	**Guam (special case in energy independence)** - *What challenges and opportunities are specific to geothermal at Guam?* Doug Blankenship, MCC2	**U.S. and worldwide military installations** - *How can geothermal be applied at DoD installations?* Valerie Browning, MCC3
12:15 pm	Networking Lunch	
Time	**Topic**	**Presenter**
1:00 pm	**Review of breakout sessions**	
2:00 pm	**Wrap-up discussion** • *Technical challenges* • *Opportunities for DARPA* o *Suggestions, Recommendations, and Action Items*	
3:00 pm	**Closing remarks**	*Speaker:* Jinendra Ranka (DARPA)
3:15 pm	Adjourn	

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(MM-YYYY)*
05-2010

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
9/1/09 – 5/31/2010

4. TITLE AND SUBTITLE
DARPA Workshop on Geothermal Energy for Military Operations

5a. CONTRACT NUMBER
W911NF-09-C-0117

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Canes, Michael E.
Lueken, Roger A.
Shepherd, Nathan J.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

LMI
2000 Corporate Ridge
McLean, VA 22102-7805

8. PERFORMING ORGANIZATION REPORT NUMBER
LMI-DRP90T1

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
DARPA
3701 North Fairfax Drive
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
A Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Defense Advanced Research Projects Agency (DARPA) sponsored a workshop March 23-25,2010,to investigate the development of geothermal energy technology for use by the U.S. military. The workshop was convened to explore whether investment in advanced geothermal technologies might reduce the risk and cost to the point where the U.S. military would be able to take advantage. The results of the workshop indicate that geothermal energy holds promise for military use under a variety of circumstances. Technological challenges, many of which were identified at the workshop, delay widespread application. The most relevant solutions from a DoD perspective likely are the advancement of Enhanced Geothermal Systems, particularly through improvements in sensor and automation technologies, and means to increase the efficiency of geothermal power production while decreasing its footprint.

15. SUBJECT TERMS
Geothermal energy, DARPA, fully burdened cost of power

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Nancy E. Handy
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	Unclassified Unlimited	62	703-917-7249

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